



Experimental Study on an Electrical Deicing Technology Utilizing Carbon Fiber Tape

Final Report



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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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ABSTRACT

In cold regions, snow and ice cause serious safety problems to transportation systems. South central Alaska, particularly Anchorage, is susceptible to a number of icing events due to frequent freeze/thaw cycles in the winter season. Traditionally, deicing has been accomplished by mechanical, chemical, and thermal means. However, these methods suffer from one or more the following shortcomings: labor intense, damage to pavement, pollution in the environment, corrosion to vehicles and reinforcing steel in concrete, and high cost. A new type of deicing system that uses commercially available carbon fiber tape is proposed. This report presents the design of a deicing heating panel, the layout and construction of a test sidewalk, experimental results and analyses, and a cost comparison with other deicing technologies. Sixteen deicing and three anti-icing experiments were conducted in the winter of 2010–2011 to examine the performance and energy consumption of the proposed system. Experimental results reported include system performance, deicing time, energy consumption, deicing cost, and temperature variation with time and location. The sensitivity of the deicing unit to ambient air temperature, wind chill, and snow density is analyzed. Finally, this system is compared with other deicing systems in terms of annual operating cost, unit energy cost, and power density. The cost comparison shows that the proposed deicing system demonstrates higher energy efficiency than its competitors and has great potential for applications in cold regions. A provisional patent application has been filed on this new deicing technology.

EXECUTIVE SUMMARY

This report describes the design and experiments of an innovative deicing technology based on the carbon fiber tape (CFT) heating panel, presents analyses of the results from deicing and anti-icing experiments, and provides a cost comparison with other deicing technologies. The main findings from this project are summarized below:

- 1) An effective resistive heating panel for roadway deicing can be assembled by using commercially available carbon fiber tape and electrodes.
- 2) The CFT heating panel-based deicing system performed satisfactorily during all deicing and anti-icing experiments conducted on a test sidewalk.
- 3) Assuming the electricity cost at \$0.2/kWh, the average energy cost for melting one inch or cm of snow was \$0.0292/[m²-cm] (\$0.0069/[ft²-in.]) for deicing experiments and \$0.0573/m²-cm (\$0.0135/[ft²-in.]) for anti-icing experiments.
- 4) Calculate in terms of operation time, the average energy cost for the CFT heating panel-based deicing system was \$0.61 per square meter per day based on all experiments.
- 5) Under the same conditions in terms of sidewalk design and heating input, the most important factor affecting deicing time and unit energy cost is the ambient temperature or wind chill, with lower ambient temperature or wind chill resulting in higher unit energy cost. Snow density is shown to have little effect on the unit energy cost.
- 6) By comparing several different deicing systems in terms of annual operating cost, unit energy cost, installation cost, and power density, the CFT heating panel-based deicing system has the lowest power density and operating cost among all the systems compared.
- 7) A provisional patent application has been filed to protect the intellectual property rights of this new deicing technology (U.S. Patent Application No. 61/699,372).

It is anticipated that after large-scale field trials, the CFT heating panel-based deicing system could find applications that include, but are not limited to, sidewalks and parking

lots in urban areas, bridge decks and road sections susceptible to icing, and street crossings and culverts that need to be operational in winter in Alaska and other cold regions.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

In cold regions, traffic accidents and a great number of injuries occur frequently due to snow and ice on sidewalks, roadways, bridge decks, and pavement. Ice on bridge decks and pavement is a persistent problem. In particular, black ice (or glare ice)—a thin, unexpected, and invisible coating of ice—occurs on roadways in coastal areas or on bridge decks spanning open water, when moisture condenses and freezes. Since black ice appears as the color of the material beneath it, the ice is difficult to notice and therefore is particularly hazardous. South central Alaska, Anchorage, is susceptible to a number of icing events due to repeated freeze/thaw cycles in the winter season (Zhang et al. 2007). Each icing event causes a large number of traffic accidents and injuries, even if maintenance crews work around the clock to mitigate its impact.

Traditional deicing has been accomplished by mechanical, chemical, and thermal methods. Removal by mechanical means alone, such as by plowing, may not be effective because the bond between ice and road pavement is strong (Yehia and Tuan 1999). Furthermore, the need for a work crew drives the cost of mechanical methods high. Traditional chemical methods, such as using sodium chloride (rock salt), are inexpensive and effective (Menzies 1991). Chemicals that are widely used in Alaska for direct deicing application or for mixing with sand and gravel to prevent them from freezing and sticking together, include sodium chloride, calcium chloride, magnesium chloride, potassium acetate, and calcium magnesium acetate (Zhang et al. 2009). MWH (2003) reports that a chloride-based chemical was used as deicer by the Municipality of Anchorage Street Maintenance Department to treat the city's streets. However, chemical methods have a strong tendency to corrode vehicles and reinforcing steel bars in infrastructure, damage vegetation, pollute groundwater, and decrease aeration and water availability in soil (Jones et al. 1992; TRB 1992; Williams et al. 2000; Shi et al. 2009b). In recent years, a number of thermal technologies have been developed, but current thermal technologies either involve a complicated installation process or are expensive to operate and maintain. The following section presents a detailed review of available deicing methods.

1.2 LITERATURE REVIEW

1.2.1 Mechanical and Chemical Methods

In mechanical ice removal, large equipment and vehicles are used to plow and scrape snow and ice from pavement. The expense of employing equipment operators is a major factor contributing to the high cost of mechanical deicing. Removing compacted snow and ice with shovels or snow blowers is not always an easy task due to the strong bond between ice and pavement. Chemical treatment helps break the bond by melting the ice (Henderson 1963). Deicing of roads has traditionally been done by a combination of mechanical and chemical methods. Salt, often mixed with sand and gravel, is spread by snowplows or dump trucks on slick roads, and the ice loosened by salting is plowed from roadways. Chloride-based salts including sodium chloride, magnesium chloride, and calcium chloride are the most common chemicals used for ice and snow control since they are inexpensive and effective (Menzies 1991). These salts, however, can corrode vehicles and reinforcing steel in the concrete and pollute the environment (Jones 1992; Williams et al. 2000; Shi et al. 2009b).

To reduce damage to concrete structures, some complex chemical solutions have been applied (Kuemmel 1994; Zenewitz 1977). In recent years, acetate-based deicers such as potassium acetate, calcium magnesium acetate, or calcium-magnesium-potassium acetate have been given preference as deicers, since they tend to decompose faster and do not contain chloride. However, acetates pose a risk to the durability of concrete and asphalt pavements and are costly (Hassan et al. 2002; Fay et al. 2008; Pan et al. 2008; Shi et al. 2009a; Shi et al. 2011). Calcium magnesium acetate (CMA) is noncorrosive to steel reinforcement, but it requires large trucks for transport, is less effective than salts, that is, it performs slower than salts, and its application temperature range is smaller (Slick 1988; Fay et al. 2008).

More recently, organic compounds generated as by-products of agricultural operations, such as sugar beet refining or the distillation process that produces ethanol, have been applied for ice and snow control. When mixed with other chloride, such as magnesium chloride, these organic compounds have longer residual effects when spread on roadways. Additionally, mixing common rock salt with some of the organic compounds and magnesium chloride results in spreadable materials that are effective at colder temperatures (-30°F/-34°C) and require lower overall rates of spreading per unit area (<http://www.magicsalt.info/Magic%20Salt.htm>). Nevertheless, organic compounds mixed

with chloride can harm the environment and are costly. It is worth mentioning that urea, a soluble nitrogen compound, is commonly used for airport pavement deicing because of its low corrosiveness.

1.2.2 Thermal Methods

A number of alternative thermal methods have been developed to control snow and ice formation on ramps and bridge decks. Yehia and Tuan (1999) have provided a comprehensive literature survey of road deicing/anti-icing methods used over the past 30 years. A brief review of thermal methods is presented here.

1.2.2.1 Pavement Deicing with Internal Heating Elements

1) Ground-Source Heat Pipe

Initial experimental testing of ground heat pipes was conducted in 1970 by Dynatherm Corporation at the FHWA Fairbanks Highway Research Station (Bienert et al. 1974). In 1975, Long and Baldwin (1980) conducted experiments using a heating system that had 1,213 ground heat pipes extending 60 ft into the ground on a highway ramp in Oak Hill, West Virginia. This system was successfully used to prevent snow and ice accumulation, except when snowdrifting occurred. The far-field ground temperature in this case averaged around 13°C. A gravity-operated heating pipe system that used a manifold ground heat exchanger was implemented in a bridge deck in 1981 in Laramie, Wyoming (Lee et al. 1984). This system used field-assembled heat pipes to transfer energy from 100 ft vertical evaporators in the ground. The results show that the heated surface was approximately 2–14°C warmer than the unheated portion of the bridge during operation, which was sufficient to prevent preferential freezing of the bridge deck surface and provided some snow-melting function. The main disadvantage was that the assembly of the heat pipes was complicated and 40% of the total cost was for drilling and grouting the pipes. Zenewitz (1977) described another example of using a geothermal source in snow and ice control in Oregon. In this case, a hot-water heating system with copper pipes containing antifreeze heated by a geothermal source was installed in reinforced concrete pavement approximately 122 m long on the deck of a canal bridge to keep the deck free of ice.

2) Hot Fluid Heat Pipe

In 1993, rubber hoses containing antifreeze heated by a gas boiler were embedded in a concrete pedestrian overpass in Lincoln, Nebraska (Cress 1995). This heating system was not in service due to a leak in the PVC supply and return lines. The installation cost of the system was \$161/m², and the operating cost per storm was about \$250 to melt 76 mm thick

snow. A heating system that consisted of steel pipes and carried Freon heated to 149°C by a propane-fired boiler was installed in the Buffalo River Bridge at Amherst, Virginia, in 1996 (ASCE 1998). This system used the latent heat released during condensation of the evaporated Freon for deicing, and the estimated annual operating cost was approximately \$1,000. Similar hydronic systems have been installed in Ohio, Oregon, Pennsylvania, South Dakota, and Texas.

3) Solar-Source Heat Pipes

Zhao et al. (2010) reported a deicing system in Japan that uses solar energy. The solar energy is collected from the road surface by a water pump when the temperature is high in summer, and is stored underground by horizontal and vertical pipes embedded in pavement. In winter, the water pump brings warm water through the pipes to the pavement for deicing. Only the water pump consumes electric energy in this system. The energy used for deicing is solar energy and a geothermal heat source.

4) Electric Heating Cable

Electric heating cables were installed on the approach and the deck of a highway drawbridge to remove snow/ice in Newark, New Jersey, in 1961 (Henderson 1963). Power density was 378 W/m² for the bridge deck and 430 W/m² for the road pavement. The heat generated by electric current was sufficient to melt 25 mm thick snow per hour. However, the installation was later abandoned because the electric cables pulled out of the asphalt-concrete overlay due to traffic load on the pavement. A similar system was installed in two ramps and a bridge deck in Teterboro, New Jersey, in 1964 (Zenewitz 1977). This system was reported to work well for deicing. The power density was about 375 W/m², and the annual operating cost was approximately \$5/m². Installation of similar systems can be found in Nebraska, Ohio, Oregon, Pennsylvania, South Dakota, Texas, and West Virginia.

5) Carbon Fiber Heating Wire

Carbon fiber wires have been used as a heating element for deicing. Zhao et al. (2010) reported a field experiment where carbon fiber heating wires were embedded in a concrete slab for a bridge deck deicing study. The slab of 1 × 2 × 0.25 m (L×W×T) was cast by using C40 concrete. Carbon fiber heating wires were wound around the reinforcing mesh longitudinally, and the interval between the reinforcing bars was 100 mm. The power density was in the range of 500–800 W/m², and the annual operating cost was in the range of \$0.375–\$2.8/m²-storm.

1.2.2.2 Pavement Deicing with External Heating Elements

1) Microwave

Hopstock (2003) conceived the idea of testing magnetite-bearing taconite aggregate and microwave technology for two potential road-use applications: (1) all-season hot-mix pothole patching and curing, and 2) chemical-free deicing of surfaces paved with asphalt concrete, including highways, bridge decks, pedestrian walkways, and airport runways. Results from a preliminary bench-scale assessment of this idea using a conventional microwave oven show that magnetite-bearing taconite aggregate is indeed an excellent microwave absorber (Hopstock 2003; Hopstock and Zanko 2005). When a truck-mounted microwave generator is driven over an ice-covered roadway constructed with crushed taconite as the aggregate, the microwaves should pass through the ice and be absorbed as heat at the road/ice interface, allowing the ice to be easily detached and scraped away. However, these findings have not been validated in a full-scale, practical testing program (Hopstock 2005).

2) Infrared Heat Lamp

An infrared heat lamp was used as an external heating element in an ice prevention system installed on the Mississippi Avenue Bridge in Denver, Colorado (Zenewitz 1977). The infrared lamps were used to heat the underside of the bridge deck with a power density of 75 W/m^2 . It was found that the heat lamp system was insufficient to prevent ice formation on the road surface due to excessive lag time and inadequate power density.

1.2.2.3 Electrically Conductive Concrete

Conventional concrete is not electrically conductive. In electrically conductive concrete, a certain amount of electronically conductive components is used to replace a certain portion of the fine and coarse aggregates to attain stable and relatively high electrical conductivity. Electrically conductive concrete (ECC) is a patented technology developed at the National Research Council of Canada (Xie et al. 1995, U.S. Patent No. 5,447,564; Pye et al. 2003, U.S. Patent No. 6,503,318 B2).

Conductive concrete can be classified into two types: fiber-reinforced conductive concrete with higher mechanical strength and lower conductivity ($100 \text{ } \Omega\text{-cm}$), and aggregate-containing conductive concrete with lower compressive strength and higher conductivity ($10 \text{ to } 30 \text{ } \Omega\text{-cm}$) (Xie and Beaudoin 1995; Xie et al. 1996). Conductive concrete cement-based composites with both high conductivity and mechanical strength were applied to melt snow/ice in the laboratory and in the field (Xie and Beaudoin 1995; Xie et al. 1996; Tumidajski 2002). A composite concrete slab consisting of a base ECC

layer and a Portland cement concrete (PCC) overlay was used to melt snow. The overlay had a w/c ratio of 0.325 and a mix design of cement/fine aggregate/coarse aggregate of 1:2:2. The dimensions of the experiment slab were $0.24 \times 0.31 \times 0.05$ m (L×W×T). For typical applications, voltages were always less than 15 V, and the primary current through the ECC layer was less than 30 A (Pye et al. 2003). The current through the overlay was extremely small (0.012 mA). Alternately, the thickness of the overlay can be increased to reduce the current through the overlay. However, the energy efficiency for snow melting will be compromised with a very thick overlay (Tumidajski et al. 2003).

Yehia and Tuan (1998) developed a conductive concrete mix with steel fibers and steel shavings specifically for bridge deck deicing. Over 50 trial mixes of conductive concrete were prepared using steel fibers and steel shavings. The heat generated by the conductive concrete was stable and uniform, using 15–20% conductive material (i.e., steel fibers and shavings) by volume. Experiments using small-scale slabs showed that the average power density of approximately 520 W/m^2 was generated by the conductive concrete, and it took 30 min to raise the slab temperature from -1.1° to 15.6°C (Yehia and Tuan 1998; Yehia and Tuan 1999). In 1998, Yehia and Tuan conducted several groups of laboratory deicing and anti-icing experiments. They found that steel shavings of 20% per volume and steel fibers of 1.5% per volume were the upper bound; higher amount of shavings or steel fibers result in poor workability and surface finishability (Yehia et al. 2000; Yehia and Tuan 2000).

Two 9 cm thick conductive concrete overlays 2×2 m large were cast on top of two 15 cm thick conventional concrete slabs 1.2×3.6 m large for conducting deicing experiments in the natural environment. Deicing and anti-icing experiments were conducted in five snowstorms in 1998. An average power density of about 590 W/m^2 was generated by the conductive concrete overlays to prevent snow and ice accumulation (Yehia and Tuan 2000). The average unit energy cost was about $\$0.8/\text{m}^2$ for each storm, with an assumed electricity cost of $\$0.08/\text{kWh}$ (Yehia and Tuan 2000; Tuan 2004).

In spring 2001, carbon products were used to replace the steel shavings in the conductive concrete. Based on the findings from laboratory tests, the conductive concrete with carbon products was applied on the deck of Roca Spur Bridge for deicing (Tuan and Yehia 2004). A 36 m long and 8.5 m wide conductive concrete inlay was built and instrumented with temperature and current sensors for heating-performance monitoring during winter storms. The inlay was divided into 52 isolated 1.2×4.1 m slabs (Tuan 2008). Three-phase 208 V, 600 A AC power was supplied to the conductive concrete slabs for deicing. All mixes contained 1.5% steel fibers and 25% carbon products per volume of the

conductive concrete. Operation of this deicing system in four winter seasons shows that power density was in the range of 203~431 W/m², and the unit energy cost was about \$250 per snowstorm, or about \$0.8/m² (Tuan 2008).

1.3 PROBLEM STATEMENT

In summary, deicing has traditionally been accomplished by mechanical, chemical, and thermal methods. These methods have drawbacks in that some of them damage the pavement, pollute the environment, and corrode vehicles and reinforcing steel in concrete, and some require complicated installation or are too expensive. There is great need for an environment-friendly anti-corrosive and cost-effective deicing technology for the broader cold region. The aim of this study was to develop an innovative, resistive heating deicing/anti-icing system based on commercially available carbon fiber tape (CFT) by taking advantage of this product's high thermal conductivity, low electrical resistance, and great strength. This report describes the assembly of a resistive heating panel, the construction of a testing facility, and experiments in deicing/anti-icing, and includes analyses of energy costs and a comparison of the proposed system with other deicing systems in terms of installation and operating cost.

1.4 STUDY OBJECTIVE

The objective of this project was to evaluate the feasibility, the reliability, and the cost-effectiveness of a CFT-based deicing system for sidewalk deicing applications.

1.5 SCOPE OF WORK

The scope of this study includes the following six tasks:

1. Design an outdoor field test sidewalk including selection of location, sidewalk layout, and configuration.
2. Design, assemble, and install CFT heating panels, construct the field test sidewalk, and connect the heating panels to the control and power supply systems.
3. Conduct deicing and anti-icing experiments under various conditions and collect data regarding the performance of the deicing system and environmental variables including ambient air temperature, wind chill, snow density, and snow accumulation.
4. Evaluate the energy cost for each deicing/anti-icing test, and analyze the factors that influence energy usage.

5. Assess the reliability of this heating system and compare the CFT heating panel-based deicing system with other heating systems in terms of installation cost and operating cost.

6. Observe and propose measures to improve the proposed deicing system for future applications.

CHAPTER 2: DESIGN OF HEATING PANELS AND A TEST SIDEWALK

2.1 INTRODUCTION

Carbon nano-fiber (CNF) paper has superior thermal, mechanical, and electrical properties and offers great potential for deicing applications. Chang et al. (2009) tested a conceptual deicing system based on CNF paper in a controlled subfreezing chamber to investigate its feasibility. The results showed promise for CNF paper to evolve into a next-generation deicing technology. Zhou et al. (2011) conducted a comprehensive numerical simulation of the CNF paper-based deicing system in a roadway application and proposed several design guidelines for large-scale experiments. It was our intention to use CNF paper in a pilot project during the proposal stage, but only one manufacturer was producing the product and on a small scale. By the time this project was officially funded, the manufacturer was not able to provide the amount of CNF paper required for the experiments, and the cost was expensive (Personal Comm., David Firsich, Inorganic Specialists, Inc., Aug. 2010). Fortunately, carbon fiber tape (CFT), which is made of regular carbon fibers, is similar to CNF. Carbon fiber tape is less superior to CNF paper, but has comparable properties; that is, it is lightweight and has high tensile strength, high thermal conductivity, and high temperature tolerance. Carbon fiber paper is commercially available and at a much lower cost than CNF paper. We decided to use CFT as the resistive heating element for deicing application.

2.2 DESCRIPTION OF CARBON FIBER TAPE

Plain woven 3-inch-wide CFT manufactured by Fibre Glast Development Corporation (2011) was used to assemble heating panels for the deicing experiments. Figure 2.1 shows three rolls of CFT with different widths. The weight and the thickness of the 3-inch-wide CFT are 5.7 oz/yd² (0.19 kg/m²) and 0.012 in. (0.03 cm), respectively. The electrical resistance of CFT 6 inches long was measured at 7.5 Ω .



Figure 2.1 Carbon fiber tape rolls

2.3 DESIGN OF CFT HEATING PANEL

Figure 2.2 shows the design of the heating panel used for the deicing experiments in this project. The dimension of each heating panel is 6×4 ft (1.8×1.2 m). The CFTs acting as resistive heating elements are attached to the copper strips, which serve as electrodes. There are eight carbon fiber strips for one heating panel. The space between adjacent CFT edges is 3 inches to ensure the integrity of the concrete pavement with the heating panel embedment.

Electrically conductive epoxy was applied in the interface between the electrodes and the carbon fiber strips to ensure good conductivity in the heating panel. To increase the safety of the system, the assembled heating panels were coated with a thin layer of thermally conductive electrically nonconductive epoxy to insulate them from the concrete sidewalk. The overall electrical resistance of the assembled heating panels ranges from 0.9 Ω to 1.1 Ω .

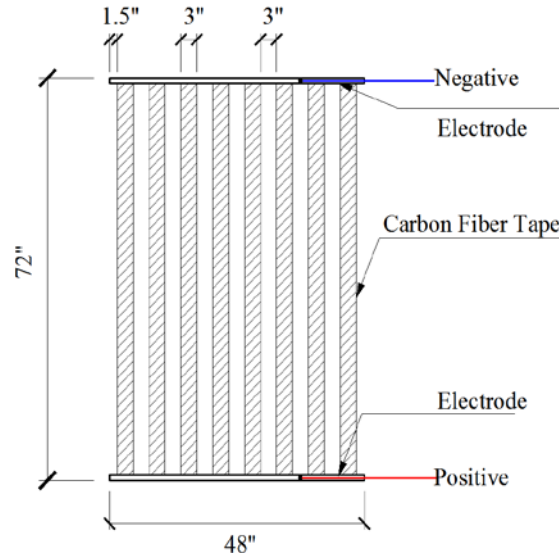


Figure 2.2 Layout of the CFT heating panel

2.4 DESCRIPTION OF THE TEST SIDEWALK

A site on the west side of University Lake Building Annex on the UAA campus was selected to build a test sidewalk for the field experiment. To assess the effectiveness of a deicing system and help determine the configuration of the test sidewalk, a finite element (FE) model was built and calibrated by the results of laboratory tests from the University of Huston, and used to evaluate the key parameters affecting the performance of a roadway deicing system, such as air temperature, wind speed, insulation layer thicknesses, and heating input (Zhou et al. 2010). Based on the results from FE analysis, the layout and configuration of the test sidewalk were determined (Figure 2.3 and Figure 2.4).

The test sidewalk, as shown in Figure 2.3, is 30 ft (9.14 m) long and 4 ft (1.22 m) wide. The entire sidewalk consists of five 6 × 4 ft (1.8 × 1.2 m) blocks. Among the five sidewalk blocks, three CFT heating panels were embedded in Block 2 to Block 4 (shaded as shown in Figure 2.3). Blocks 1 and 5 served as the control group. The cross-section of the testing sidewalk (A-A section) is shown in Figure 2.4. Above the base coarse material of the sidewalk, 2-inch-thick Extruded Polystyrene (XPS) foam boards were installed to provide insulation for the entire concrete sidewalk. The total thickness of the sidewalk pavement at

the downslope end is 4 in. (10 cm), with a 1% slope in the sidewalk surface for water drainage. The CFT heating panels were located 1 inch above the bottom of the sidewalk.

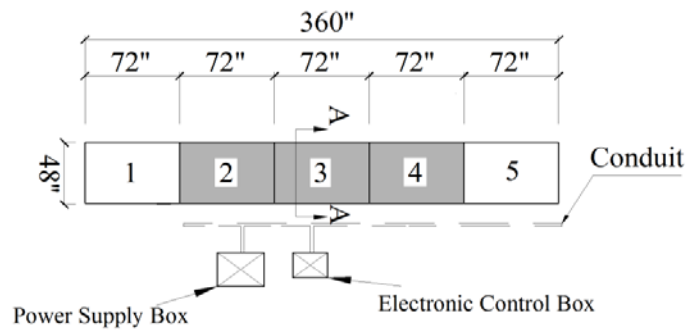


Figure 2.3 Plan view of the test sidewalk

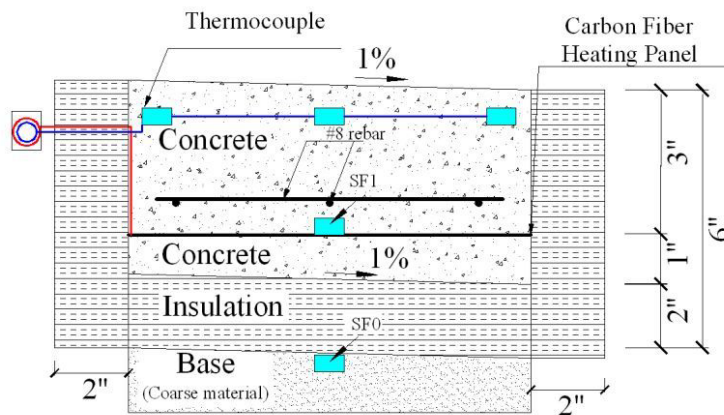


Figure 2.4 A-A section of the test sidewalk (SF1 and SF0 are thermocouples used to monitor heating panel and soil temperature, respectively)

2.5 TEMPERATURE MONITORING SYSTEM

To monitor the performance of the deicing system, thirteen thermocouples were used to record the temperature at various locations in the test sidewalk. In Block 3, two thermocouples labeled SF1 and SF0 (see Figure 2.4) were installed on the surface of the heating panel and on the bottom of the insulation board, respectively, to obtain temperature profiles during deicing experiments. Thermocouples labeled T1 to T11, as shown in Figure 2.5, were installed near the top surface of Blocks 2 to 4 to monitor the temperature distribution on the sidewalk surface.

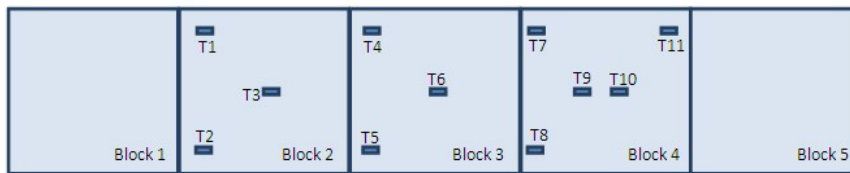


Figure 2.5 Distribution of thermocouples T1–T11 on the surface of the sidewalk

CHAPTER 3: IMPLEMENTATION OF THE DEICING SYSTEM

3.1 ASSEMBLING THE CFT HEATING PANEL

The assembly of the CFT heating panel was crucial to the success of this project. A procedure was envisioned and improved after several trials, and the heating panels used in this experiment were made by strictly following this procedure to ensure consistency in each heating panel. The main assembly process included the following nine steps.

1) Making Frames

Rectangle frames of 6×4 ft (1.8×1.2 m) were made with timber strips, as shown in Figure 3.1, to facilitate assembly of the CFT heating panels. The desired positions of the CFT were marked on the frame.

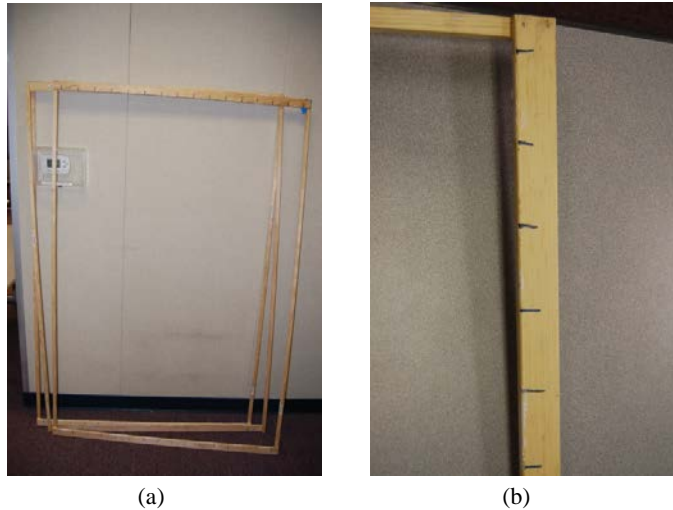


Figure 3.1 Rectangle frames: (a) overall view; (b) marks for positioning CFTs

2) Cutting Carbon Fiber Tape

Considering the length of the heating panel and the extra length needed for interfacing with the electrodes, the CFTs were cut into strips 74 inches long, as shown in Figure 3.2. Masking tape was used across the width of the carbon fiber strips (on one side) to prevent frayed ends.

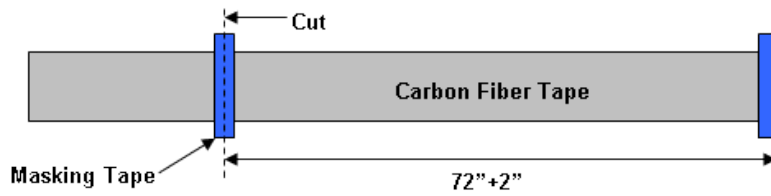


Figure 3.2 Cutting carbon fiber tape into strips

3) Tightening and Attaching Carbon Fiber Strips on Frame

As shown in Figure 3.3, each carbon fiber strip was tightened and attached to the rectangular frame with reference to the marks on the frame. Each frame has eight carbon fiber strips placed parallel to each other. When the carbon fiber strips were attached to the frame, masking tape was used to cover the ends of the carbon fiber strips where the electrodes would be attached. Masking tape was used to protect the carbon fiber strips from the epoxy coating, which would be carried out in the next step, and to ensure good contact and hence high conductivity at the interface of the carbon fiber strip and electrode.



Figure 3.3 Tightening and attaching carbon fiber strips on the frame

4) Coating Carbon Fiber Strips with Epoxy Resin

A thin layer of thermally conductive, electrically nonconductive epoxy resin was coated on the surface of carbon fiber strips for two reasons: 1) to form a carbon fiber composite to maintain a stable pattern in the carbon fiber strips during handling and installation, and 2) to package the heating element to prevent electrical leakage during operation and provide an effective thermally conductive interface between the heating

panel and the sidewalk. The epoxy resin was applied on both sides of the carbon fiber strips. Figure 3.4 shows a frame with carbon fiber strips being coated with epoxy resin using paint scrapers and brushes. Note that epoxy resin should not be applied on the second side of the carbon fiber strips until the epoxy resin has cured on the first side, as discussed in the next step.



Figure 3.4 Coating the carbon fiber strips with epoxy resin

5) Curing the Carbon Fiber Strips Coated with Epoxy Resin

The carbon fiber strips with a fresh coating of epoxy resin were cured by placing them in a controlled environment chamber at about 105°F (40°C) for at least 24 hours before directly contacting the coated surface.

6) Preparing Copper Strips

For each heating panel, two copper strips were used to form electrodes. The copper strips were cut to a length of 47 inches (1.2 m), which is 1 inch shorter than the width of the sidewalk. The reason for this difference in length was to make sure that the copper strips could be installed in the mold formed for the sidewalk construction. The desired positions of the carbon fiber strips were marked on the copper strips as well.

7) Attaching Electrodes to Carbon Fiber Strips

After the epoxy resin coating on both sides of the carbon fiber strips was fully cured, the carbon fiber strips were removed from the wood frames.

Electrically conductive epoxy was used to ensure good contact between the copper strip and the carbon fiber strip. A thin layer of epoxy was first spread across the electrode attachment area evenly. Within the epoxy's working time, copper strips were laid onto the

epoxy at the designed location, and carbon fiber strips were wrapped around the copper strips. Note that pressure should be applied evenly over the copper strips to ensure their bond with the carbon fiber strips.

After allowing the epoxy to fully cure, copper strips with eyelets were placed on one side of the copper strips, and nails were used to enhance the connection between the carbon fiber strips and the copper strips, as shown in Figure 3.5.



(a)



(b)

Figure 3.5 Close-up of the connection between the carbon fiber strips and the electrode

8) Attaching Power Supply Cables to Electrodes

As shown in Figure 3.6, power supply cables were attached to the copper electrode strips, by bolts through the drilled holes. Anti-oxidant joint compound was used to fill the gaps between the cables and the copper electrodes to ensure good electrical conductivity.



Figure 3.6 Connection of power cable with copper electrode

9) Applying Finishing Coat on the Heating Panel

After all of the connections were completed, thermally conductive electrically nonconductive epoxy resin was applied on the copper electrodes. A finishing epoxy resin coating was also applied to make sure the entire heating panel, including the carbon fiber strips and electrodes, was fully insulated in the sidewalk.

3.2 CONSTRUCTION OF THE TEST SIDEWALK

The test sidewalk with a conventional Portland cement concrete (PCC) surface was constructed in September 2010 on the UAA campus. A layer of coarse material (sandy gravel) was compacted as the base of the test sidewalk, as shown in Figure 3.7. A 2-inch-thick Extruded Polystyrene (XPS) insulation board (see Figure 3.8) was laid at the bottom and the sides of the prepared site to provide a layer of insulation for the sidewalk.



Figure 3.7 Site preparation



Figure 3.8 Site with a mold and an insulation layer in place

Figure 3.9 shows that 1-inch-thick concrete was first laid on the insulation layer to provide a base for the CFT heating panel. After laying the heating panels on the concrete, as shown in Figure 3.10, a rebar mesh with 1.5×1.5 ft (0.46×0.46 m) openings made of #8 rebar was installed 1 in. (0.025 m) above the heating panels. Another layer of concrete 3 in. (0.076 m) thick was poured onto the CFT heating panel, as depicted in Figure 3.11. The completed sidewalk is shown in Figure 3.12.



Figure 3.9 Preparing a base for the CFT heating panel



Figure 3.5 Installing the CFT heating panel



Figure 3.6 Pouring cover concrete



Figure 3.7 View of the completed sidewalk

The concrete sidewalk was designed by following the concrete standards defined in the Municipality of Anchorage Standard Specifications (MASS). A Type-2 concrete with 6% entrained air content and a water/cement ratio of 0.495 was used in the test sidewalk construction. The specifics of the concrete are listed in Table 3.1.

Table 3.1 Materials used in concrete mix

Material	Design Quantity	Required	Batched	% Difference	Moisture Variation	Total Water Content
TYPE 1 CEM	564 lb	1128 lb	1130 lb	0.18%		
3/4 ROCK	1759 lb	3551 lb	3560 lb	0.25%	0.95%	4
3/8 PEA	92 lb	187 lb	200 lb	6.95%	1.90%	
CONSAND	1228 lb	2549 lb	2580 lb	1.22%	3.80%	11
WATER	279.6 lb	387.2 lb	390 lb	0.72%		48.7
AIR	4.8 oz	9.6 oz	9 oz	-6.25%		
NC 534	56.4 oz	112.8 oz	112 oz	-0.71%		

3.3 CONSTRUCTION OF THE FIELD EXPERIMENT FACILITY

Besides the sidewalk with embedded CFT heating panels, two boxes—the power supply box and the data acquisition/control box—house the power supply and data acquisition/control systems of the field experiment facility, as shown in Figure 3.8.



Figure 3.8 The deicing test facility

3.3.1 Power Supply Box

The power supply system consists of a power meter, three step-down transformers, and relays, as shown in Figure 3.9. Power and energy usage can be tracked by the power meter. The transformers used in this deicing system have a primary voltage of 120/240 V, a

secondary voltage of 12/24 V, and a power rating of 1000 VA. The transformers were connected to a 110V/60 Hz alternating current (AC) power outlet, and the heating panels were charged with a 24 V AC for heat generation. The three heating panels were powered and controlled individually. Figure 3.10 shows the wiring diagram of the power supply system.

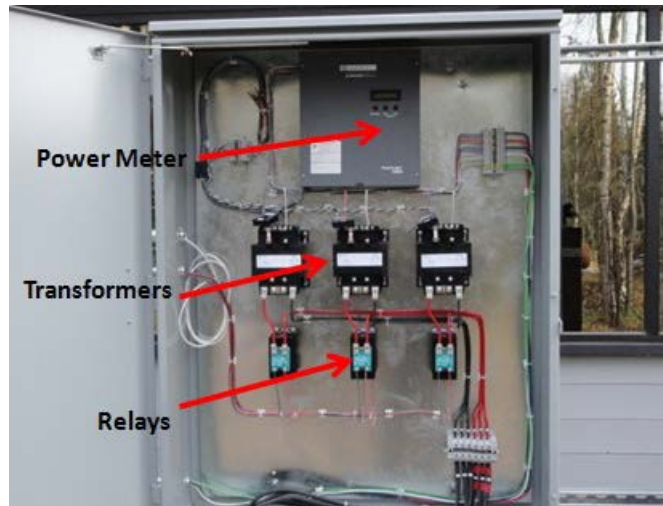


Figure 3.9 Inside of the power supply box

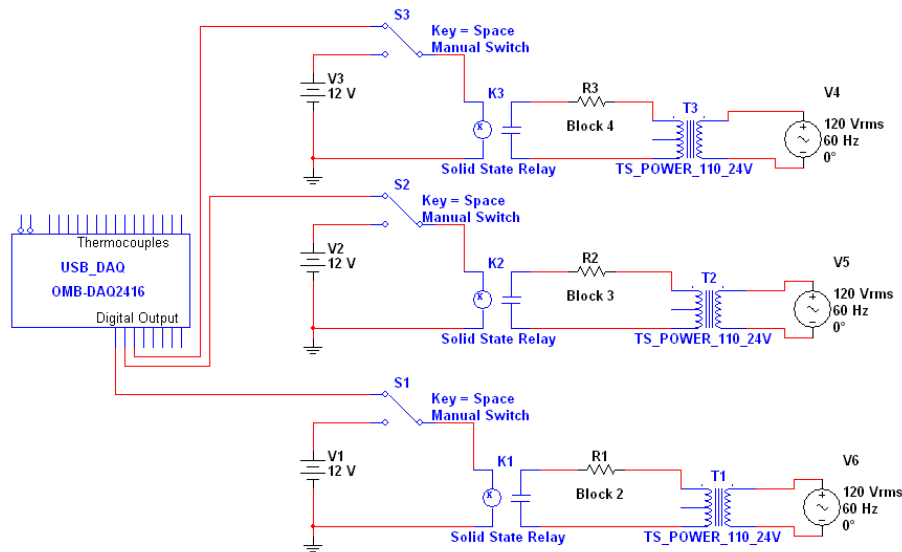


Figure 3.10 The wiring diagram of the power supply system

3.3.2 Data Acquisition and Control Box

The data acquisition/control box houses three units: a temperature-sensing unit, a data-acquisition unit, and a power-switching unit (Figure 3.11). As discussed in Section 2.5, thirteen thermocouples were installed at various locations in the sidewalk to monitor the temperature. Data acquisition was accomplished by a CR3000 Micrologger (see Figure 3.12). These temperature data were recorded at one reading per five seconds, and then the average temperature was recorded at a frequency of one data point per minute. The data were retrieved through an office computer via the Internet. In the current setting, power switches were used to manually control the power supply (Figure 3.13). In the near future, an automatic control system will replace the manual control system in this deicing system.

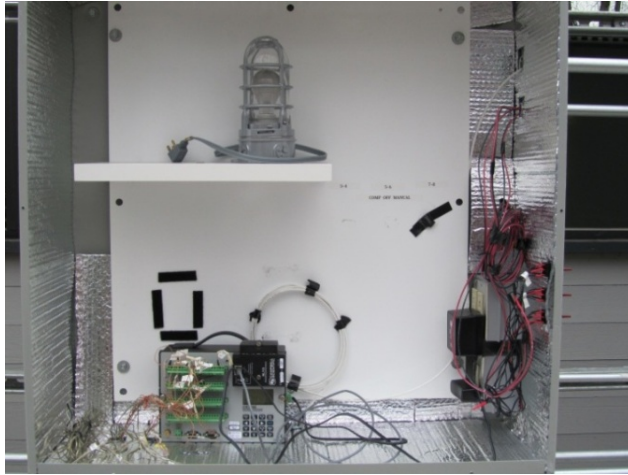


Figure 3.11 The electronic control box



Figure 3.12 The CR3000 micrologger for data acquisition



Figure 3.13 Power switches for manual control of the deicing system

CHAPTER 4: EXPERIMENTAL RESULTS AND ANALYSES

4.1 FIELD EXPERIMENTS

Two types of experiments—deicing and anti-icing—were conducted using the test facility described in the previous chapter. In a deicing test, the system is turned on after snow accumulation is observed on the sidewalk, and the system is turned off when the snow/ice has completely melted and the water has drained off.

In an anti-icing test, the system is turned on in anticipation of an icing event or a snowstorm, and the system is turned off when the event ends. These tests were conducted under various ambient temperatures and wind speeds. During the 2010–2011 winter season, 16 deicing tests and 3 anti-icing tests were conducted on the test sidewalk.

4.2 PERFORMANCE OF THE CFT HEATING PANEL TECHNOLOGY IN DEICING EXPERIMENTS

Figure 4.1 shows an example of the deicing experiment conducted on January 12, 2010. The appearance of the test sidewalk during the deicing experiment is shown in Figure 4.1 (a) to (c). The snow accumulation was 1.57 cm with a density of 401.12 kg/m³. The average air temperature during the test was 11.5°F (-11.4°C); the corresponding wind chill was -6.3°F (-21.3°C). It took 9.3 hours to melt the snow on the sidewalk.

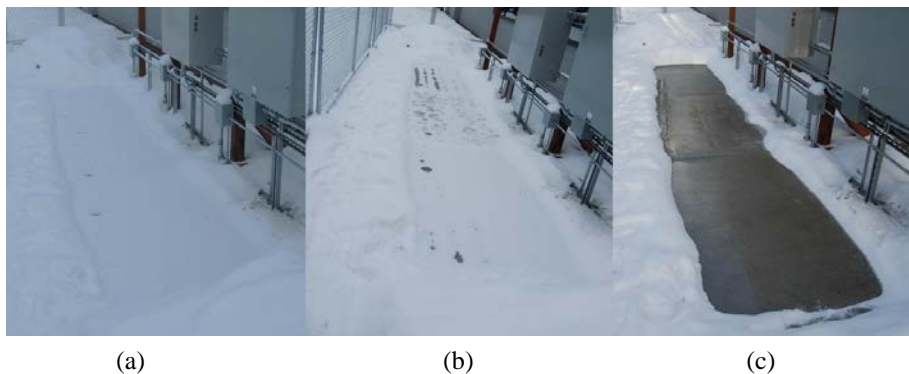


Figure 4.1 The performance of the deicing experiment: (a) test sidewalk before deicing
(b) test sidewalk during deicing, (c) test sidewalk after deicing

Figure 4.2 shows temperature variation with location and time during the same deicing experiment pictured in Figure 4.1. The five selected locations include the heating panel surface (Thermocouple SF1) and the base coarse material right beneath the insulation

board (Thermocouple SF0), and the lower side (Thermocouple T6), middle (Thermocouple T5), and upper side (Thermocouple T4) of the sidewalk surface slope. The lowest air temperature was -9.4°F (-23.0°C), and occurred early in the morning. The initial temperature of the entire sidewalk was 4.1°F (-15.5°C).

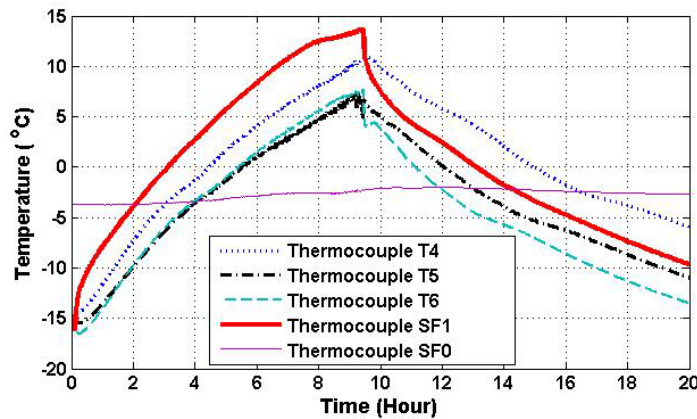


Figure 4.2 Temperature variation during the deicing experiment of January 12, 2011

Figure 4.2 shows that after the power was turned on, the sidewalk surface temperature dropped slightly due to the initial temperature gradient and then started to rise, as predicted by Zhou et al. (2011). Within 4.5 hours, the temperature on the lower side of the surface rose to above the melting point of snow. The time required for the snow to melt and the water to drain from the sidewalk surface was 7.5 hours. During the experiment, the sidewalk surface temperature peaked at 51.8°F (11°C). The temperature difference observed at different locations of the sidewalk surface was within 5.4°F (3°C), indicating that the panels heated the sidewalk surface quite uniformly. The temperature variation of the sloped sidewalk surface is likely due to the variation in the vertical distance from the heating panel, and the thermocouple's location in relation to the discontinuous heating tape in the heating panel. During this deicing experiment, the heating panel surface temperature reached 57.2°F (14°C), and the temperature of the base coarse material below the insulation board remained around 24.8°F (-4°C), indicating that the insulation layer worked well in directing the heat toward the upper surface.

4.3 PERFORMANCE OF THE CFT HEATING PANEL TECHNOLOGY IN ANTI-ICING EXPERIMENTS

In the three anti-icing experiments conducted, the system worked very well, and no snow accumulation was observed during these experiments. For instance, on February 17, 2011, a snowstorm was forecasted by NOAA to arrive at the Anchorage area during the night. At 6:00 p.m. on February 17, the deicing system was turned on. The snow began falling around 10:30 p.m. and continued well into the day of February 18. The total accumulation was about 6 inches. No web camera was set up on-site to take snapshots during the storm the night of February 17. However, starting at 7:00 a.m. on February 18, and until the system was turned off around 7:00 p.m. the same day, no snow accumulation was observed on the sidewalk. Figure 4.3 shows one scene of the test sidewalk, with snow still falling.



Figure 4.3 The performance of the anti-icing experiment on February 17–18, 2011

Figure 4.4 shows temperature variation with location and time during the anti-icing experiment. The initial temperature of the entire sidewalk was 11.84°F (-11.2°C). As shown in Figure 4.4, it took four hours for the deicing system to raise the temperature on the lower side of the surface from -11.2°C to the snow melting point (0°C). From the temperature-versus-time curves of thermocouples T7, T8, and T9, it can be seen that for the first five hours the slope of these curves is steeper than for the next 15 hours, indicating that the snow started 5 hours after the system was turned on. This snowstorm lasted 20 hours, and the entire anti-icing experiment lasted 24 hours. The temperature difference

observed at different locations of the sidewalk surface was within 6.3°F (3.5°C). In this anti-icing experiment, the highest temperature at the heating panel was about 79.0°F (26.1°C), and the sidewalk surface temperature reached a peak value of 59.0°F (15°C). The average air temperature was 20.0°F (-6.7°C), and conditions were calm. Figure 4.4 indicates that there is noise in the temperature data of Thermocouple SF0 due to the electromagnetic interference of the AC power in the heating panel and this thermocouple's proximity to the CFT heating strips. Nonetheless, the figure shows that the temperature of the base coarse material below the insulation board remained in the range of 24.8°F (-4°C) to 28.0°F (-2°C). The cost for this anti-icing operation for the three blocks was 20.7 kWh, or \$4.1 at \$0.2/kWh.

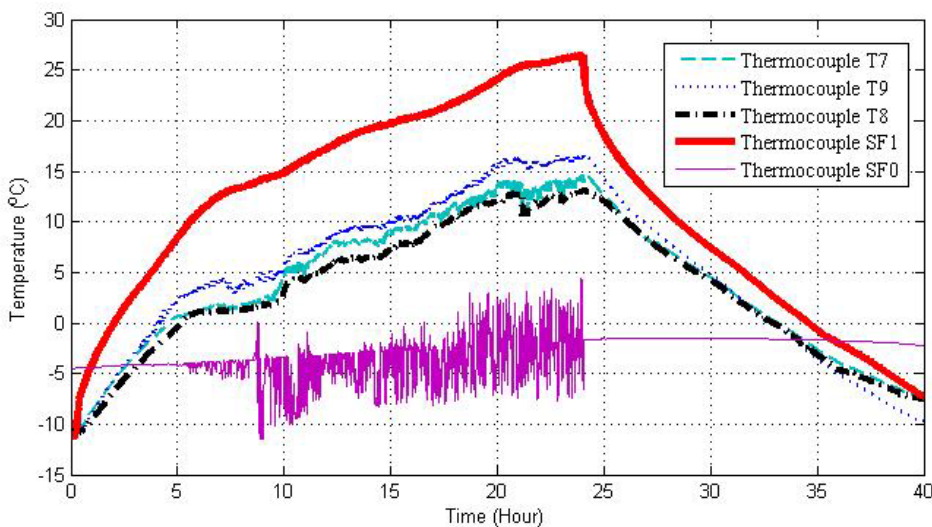


Figure 4.4 Temperature distributions in the test sidewalk during the anti-icing experiment conducted on February 17–18, 2011

4.4 SUMMARY AND DISCUSSION

During the 2010–2011 winter season, thirteen deicing experiments and three anti-icing experiments were conducted. The deicing system worked very well in each deicing and anti-icing experiment. In the next several years, more experiments will be conducted to test the reliability and energy efficiency of the deicing system. After the 2010–2011 winter season, the test sidewalk was carefully examined. No cracks were observed on the sidewalk surface. As for the heating panels, only a very small fluctuation was observed in

their electrical resistance during the one-year period after installation, as shown in Table 4.1. Overall, data indicate that the heating panels, the power supply electrodes, and the interface between the electrodes and the CFTs are quite stable. The stability of the heating panel in terms of resistance will continue to be monitored during Phase II of the study.

Table 4.1 The resistance of heating panels (Unit: Ω)

Date	Block 2	Block 3	Block 4
09/16/2010	1.2	1.3	1.2
09/17/2010	1.1	1.1	1.1
09/24/2010	1.3	1.2	0.9
09/29/2010	1.1	1.1	0.9
10/04/2010	1.2	1.2	1
10/11/2010	1.2	1	0.9
10/14/2010	1.1	1	1
11/25/2010	1.1	1	0.9
12/01/2010	1	1	1
02/17/2011	0.9	1.1	1
04/17/2011	1	1	1
05/09/2011	0.9	1	0.9
07/03/2011	1	0.9	1.1
08/05/2011	1	0.8	0.9
09/07/2011	1.1	0.9	0.9
10/12/2011	1.1	1	0.9
11/01/2011	1.1	1	0.9

CHAPTER 5: ENERGY CONSUMPTION AND COST ANALYSES

5.1 INTRODUCTION

For each experiment, a variety of data, including time usage, snow thickness, snow density, air temperature, wind speed, and energy consumption were recorded and listed in Table 5.1. Based on the information summarized in Table 5.1, the normalized snow accumulation expressed in thickness was calculated with reference to a constant snow density for comparison purposes. Wind chill was also considered to account for the effect of wind on the energy consumption of the deicing system. The normalized energy usage and unit energy cost define the energy consumption and cost per unit surface area per unit thickness of snow, respectively.

Table 5.1 Deicing experiments in the winter of 2010

Date	Time Usage (hour)	Ambient Temperature (°C)	Wind Chill (°C)	Average Density (kg/m ³)	Snow Accumulation (cm)	Snow Accumulation (Normalized) (cm)	Energy Usage (kwh)	Unit Energy Usage (kwh/m ² -cm)	Unit Energy Cost (\$/m ² -cm)
12/13/2010	10	-12.98	-15.8	510.58	2.54	21.61	8.53	0.176995	0.035399
12/15~16/2010	17	-9.57	-18.1	237.18	5.08	20.08	14.45	0.322721	0.064544
12/22/2010	13	-17.67	-24.2	203.52	1.27	4.31	10.99	1.143674	0.228735
12/29/2010	6.5	-10.52	-11.2	62.94	3.56	3.73	5.54	0.666641	0.133328
01/05/2011	5	-2.70	-3.0	410.36	1.49	8.86	4.20	0.212613	0.042523
01/06/2011	7.5	-6.96	-7.2	470.14	1.47	12.34	6.32	0.229799	0.045960
01/12/2011	12	-11.36	-21.3	401.12	1.45	10.53	10.16	0.432988	0.086598
01/13/2011	13	-14.91	-18.1	465.86	1.69	12.82	11.14	0.389791	0.077958
01/20/2011	8	-7.99	-10.9	94.44	5.08	8.00	6.86	0.384564	0.076913
01/24/2011	5	-2.79	-5.1	104.91	2.54	4.44	4.24	0.427682	0.085536
01/26/2011	3	-3.83	-4.9	913.41	0.16	2.36	2.61	0.496272	0.099254

Date	Time Usage (hour)	Ambient Temperature (°C)	Wind Chill (°C)	Average Density (kg/m ³)	Snow Accumulation (cm)	Snow Accumulation (Normalized) (cm)	Energy Usage (kwh)	Unit Energy Usage (kwh/m ² -cm)	Unit Energy Cost (\$/m ² -cm)
01/28/2011	4.72	-7.58	-11.8	915.57	0.16	2.40	4.03	0.751418	0.150284
02/02/2011	5	0.43	-2.3	109.66	5.08	9.28	4.31	0.207960	0.041592
02/03/2011	4.5	-4.71	-7.6	155.21	3.05	7.88	3.89	0.221157	0.044231
02/14/2011	9	-10.00	-11.3	99.19	2.80	4.62	7.74	0.751565	0.150313
*02/17~18/2011	24	-6.67	-6.7	82.64	11.18	15.39	20.69	0.602737	0.120547
03/18/2011	5	0.67	0.7	68.06	8.89	10.08	4.36	0.193690	0.038738
*03/30~31/2011	12.5	-1.67	-6.0	40.20	3.81	2.64	10.95	1.859141	0.371828
*04/05/2011	3	2.22	2.2	52.59	11.43	10.02	2.60	0.116182	0.023236

Note: * indicates anti-icing experiment.

+ Energy cost assumed at \$0.2/kWh based on the actual cost of electricity in 2011.

5.2 ENERGY CONSUMPTION

Air temperature indicates the average ambient air temperature recorded during each deicing experiment at one or two readings per hour. The measured snow density from different experiments varied from 40 to 510 kg/m³ due to factors such as snow accumulation time and wetness. For comparison, snow accumulation was normalized by using Equation 5.1.

$$A_N = \frac{\rho_f \cdot A_f}{\rho_{60}} \quad (5.1)$$

where A_N is snow accumulation normalized to an equivalent depth of fresh snow with a density of 60 kg/m³; ρ_f is the factual average density of snow on the test sidewalk; A_f is the factual snow accumulation on the test sidewalk; and ρ_{60} is 60 kg/m³ that is the reference fresh snow density.

Unit energy consumption is the energy consumption normalized by surface area and the equivalent snow accumulation by using Equation 5.2. Unit energy consumption indicates the energy usage for melting fresh snow of unit thickness on a unit area.

$$J_U = \frac{P}{s \cdot A_N} \quad (5.2)$$

where J_U is the unit energy usage for melting one centimeter thick snow on one square meter area with a density of 60 kg/m³; P is the power usage for one deicing/anti-icing experiment; s is the total area of three test blocks; and A_N is the normalized snow accumulation.

Assuming an electricity cost of \$0.2/kWh, the unit energy consumption was converted to unit energy cost by using Equation 5.3.

$$C_U = J_U \times \$0.20/kwh \quad (5.3)$$

where C_U is the unit energy cost for melting one square meter area by one centimeter thick snow with a density of 60 kg/m³.

As listed in Table 5.1, based on the experiments we conducted, the average unit energy cost was \$0.0292/m²-cm (\$0.0069/ft²-in) with the variance 0.00032 for all deicing experiments and \$0.0573/m²-cm (\$0.0135/ft²-in) with the variance 0.0036 for all anti-icing experiments. The cost of the anti-icing experiment conducted in March 2011 is an outlier compared with other experiments. That is mainly because the snow started to fall much later than anticipated, and the deicing system ran about 9 hours ahead of the snowstorm.

The total snow accumulation was quite small, for example, 3.81 cm compared with the other two anti-icing experiments.

It may be worthy to evaluate the energy cost in terms of operation time. If the total energy and cost is computed for all the nineteen experiments, and the total operation time is found by adding the experiment time for each test, we can find the average energy consumption and cost per day per unit area of sidewalk. This will be useful in estimating operating cost of applying this deicing system. It is found that the average energy consumption is 3.07 kWh/[m²-day] and the average energy cost is \$0.61/[m²-day].

It is anticipated that in the future this system will operate with an automatic control scheme that maintains the sidewalk surface temperature within a range of +35~40°F (+1.7~4.4°C) during any anti-icing operation, which may reduce the energy consumption substantially.

5.3 FACTORS INFLUENCING ENERGY COST

Under the conditions that variables such as thickness of the sidewalk, thickness of the insulation layer, and surface heating input remain unchanged, the most important factor that affects deicing time and unit energy cost is the temperature, that is, ambient temperature or wind chill. The unit energy cost of each deicing/anti-icing experiment under various ambient temperatures or wind chill is presented in Figure 5.1 and Figure 5.2, respectively. These figures show that deicing energy cost varies with ambient temperature or wind chill, and generally increases as the latter two decrease. The lower the air temperature or wind chill, the more heat and longer time will be needed to melt snow and ice.

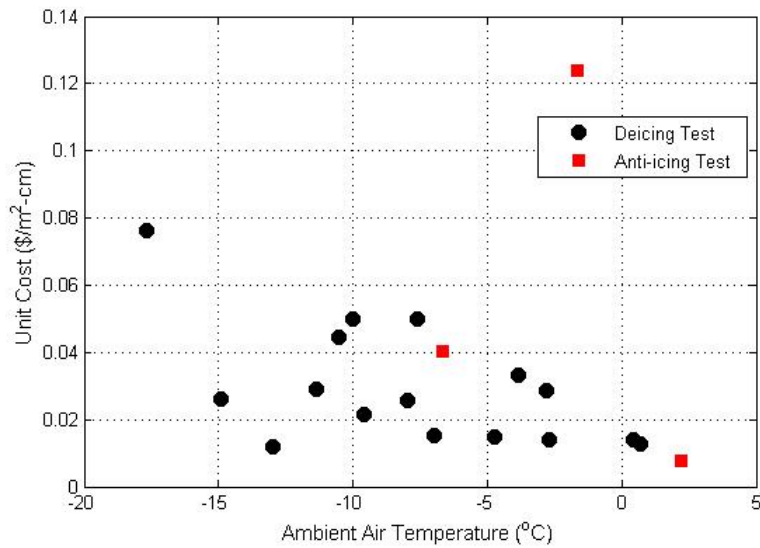


Figure 5.1 Ambient air temperature vs. unit energy cost for all deicing/anti-icing experiments

It was suspected that the density of snow affects deicing efficiency. The relationship between unit energy cost and snow density is presented in Figure 5.3, which shows that no obvious relationship between snow density and unit energy cost can be observed with available data.

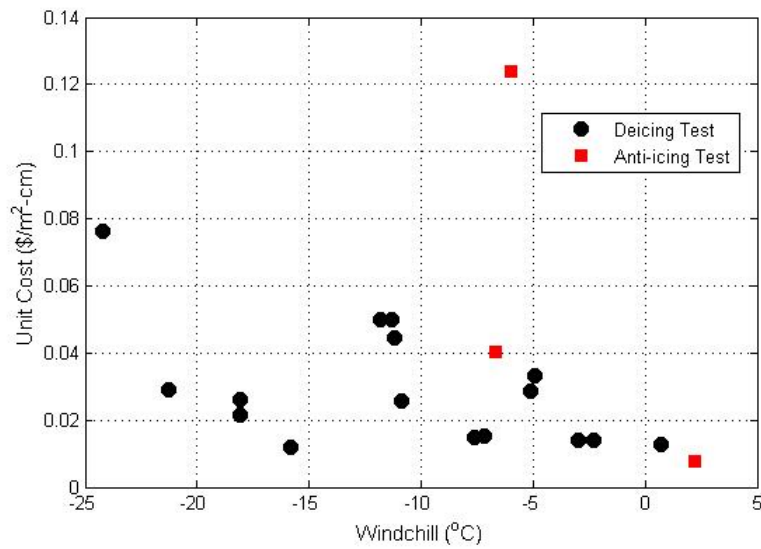


Figure 5.2 Wind chill vs. unit energy cost for all deicing/anti-icing experiments

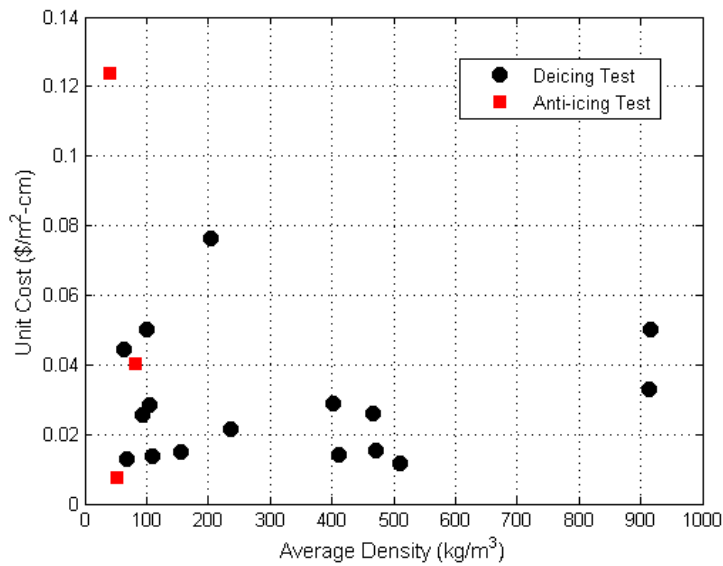


Figure 5.3 Snow density vs. deicing unit energy cost for all deicing/anti-icing experiments

5.4 COST COMPARISON

Cost-effectiveness has always been an important factor affecting the applicability of a deicing system. The present system is compared with other systems that have been reported in the literature in terms of costs, including both installation cost and operation cost, and power density. As discussed in the previous section, the deicing cost is very sensitive to air temperature. The experiments conducted in the present study had air temperatures that varied from 0–36°F (-17.7–2.2°C), while the data of other deicing systems reported in the literature were for a narrower air temperature range. To make a reasonable cost comparison, it is necessary to select an air temperature range, say from 21–27°F (-6–3°C), for comparing average unit energy cost with other systems.

Table 5.2 compares the various reported deicing systems with the current system in terms of installation cost, annual operating costs, power density, and unit energy cost. The operating cost per storm is defined as the average cost for operating a deicing system to melt snow on a unit surface area (m^2) during each deicing/anti-icing experiment. The annual operating cost indicates the average operating cost of all deicing and anti-icing experiments conducted during one year. Note that the electricity cost was assumed to be \$0.08/kWh in order to compare all systems reported in the literature on the same basis.

The installation cost for the present system was calculated based on the sum of the costs of the heating panels, electrical and control equipment, and insulation boards used in the three 6×4 ft test sidewalk blocks. It did not include the labor cost and the cost of the sidewalk materials. For the electric heating cable system (Henderson 1963), the cost of the installation was calculated in such a manner as to integrate the cost of laying the cable, installing electrical and control equipment including transformers, and electric service facilities. For the conductive concrete heating system (Tuan 2008), the installation cost includes the cost of building and installing control facilities, and the cost of integrating and programming the deicing operation controller. For the hot water deicing system reported by Cress (1995) and the conductive concrete deicing system reported by Yehia and Tuan (1999), the installation costs were quoted directly from the literature. The installation cost of the carbon fiber heating wire system reported by Zhao et al. (2010) was not available and was not considered in the cost analysis.

Table 5.2 Cost comparison of different deicing systems

Deicing System	Installation Cost (\$/m ²)	Annual Operating Cost (\$/m ²)	Power Density (W/m ²)	Unit Energy Cost at -6 – -3°C air temp. (\$/[m ² -cm])
Electric heating cable, 1961 (Henderson, 1963)	^b \$23.6/m ²	^b \$2.8/m ²	^b 323–430	^b 0.368
Hot Water, 1993 (Cress, 1995)	^a \$161/m ²	^a \$250/storm	^a 473	N/A
Conductive concrete mixing with steel shaving and steel fiber (Yehia and Tuan, 1999)	^a \$48/m ²	^a \$0.8/m ² /storm	^a 590	^b 0.075
Conductive concrete mixing with Steel Fibers and Carbon Particles, 2003-2007 (Tuan, 2008)	^b \$205/m ²	^b \$0.74/m ² /storm	^a 350	^b 0.033
Carbon Fiber Heating Wire, 2008 (Zhao et al., 2010)	N/A	^b \$0.38–\$2.8/m ² /storm	^a 500–800	^b 0.025
Carbon Fiber Tape Heating Panel (This study)	\$145/m ²	\$0.09/m ² /storm	127	0.010

Note:

- 1) ^a Cost value and power density were quoted directly from the literature.
- 2) ^b Cost value and power density were converted into uniform unit.
- 3) Energy cost was assumed at \$0.08/kWh for comparison.

It can be seen in Table 5.2 that the present system has the lowest power density and unit energy cost, and a relatively lower installation cost among the systems compared. The high efficiency of the present system is likely due to the use of an insulation layer, and the system's rather uniform heating coupled with its low power density. For applications in Alaska, the average air temperature will be lower than -6°C, and the unit energy cost will be higher. Table 5.1 shows that when the air temperature is below -6°C, at an electricity

cost of \$0.08/kWh, the average unit energy cost of the present system is around \$0.014/[m²-cm]. The data show that the CFT-based deicing system has the potential to become a very cost-effective deicing technology in the future.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A carbon fiber tape (CFT) heating panel-based deicing system was designed, assembled, and installed in a test sidewalk. Sixteen deicing and three anti-icing experiments were conducted to examine system performance and energy consumption during the winter of 2010–2011. The results from limited experiments conducted that winter show that the CFT heating panel-based deicing system performed satisfactorily on a sidewalk during all deicing and anti-icing experiments. Assuming an electricity cost of \$0.2/kWh, the average energy cost for melting one cm or inch of snow was \$0.0292/[m²-cm] (\$0.0069/[ft²-in.]) for all deicing experiments and \$0.0573/[m²-cm] (\$0.0135/[ft²-in.]) for all anti-icing experiments. Calculated in terms of operation time, the average energy cost was \$0.61/[m²-day] based on all experiments.

Under the same parameters in terms of the thickness of the sidewalk, the thickness of the insulation layer, and surface heating input, the most important factor affecting deicing time and unit energy cost is ambient temperature or wind chill; lower ambient temperature or wind chill results in higher unit energy cost. Snow density is shown to have little effect on the unit energy cost.

By comparing several different deicing systems in terms of annual operating costs, unit energy cost, installation cost, and power density, we found that among all the systems compared, the CFT heating panel-based deicing system has the lowest power density and operating cost based on the limited cases considered in this pilot project.

A provisional patent application has been filed to protect the intellectual property rights of this new deicing technology. The U.S. Patent Application is No. 61/699,372. A full patent application will be completed at an appropriate time before the expiration of the provisional patent.

6.2 RECOMMENDATIONS

Based on the findings from this report, the following topics are recommended for further study:

1. An automatic temperature-control system should be integrated with the deicing system. The automatic temperature-control system can be set to maintain the sidewalk surface within a temperature range of +35–40°F (+1.7–4.4°C). For an anti-icing experiment, such an automatic temperature-control system may reduce the energy

consumption by one-half to two-thirds of what was consumed in the deicing experiments reported in this study.

2. In the present deicing system, one transformer was applied for each heating panel. In fact, if there are many heating panels in a deicing system, it is better to apply one transformer for three or four heating panels. Doing so will simplify the wiring of the power supply system and the control system.

3. A high-resolution webcam should be set up on the site to take snapshots and aid in monitoring sidewalk performance during each deicing/anti-icing experiment, especially during nighttime operations.

4. The cables used to supply electric current to the deicing system are too stiff to handle during installation. Other more-flexible cables should be used in the future.

5. The heating panel assembly procedure and installation can be optimized. For instance, if the cables were attached to the heating panel after it was placed in the mold, installation would be easier and extra stress would be released from the cable.

6. For the present carbon fiber tape-based heating system to be implemented in practice, the following problems related to the integration of the heating panels and the sidewalk should be investigated: the impact of the embedded carbon fiber heating panel on the structural/mechanical performance of the sidewalk/driveway; the survivability of the heating panel in sidewalk cracking; the effect of temperature on internal stresses in a rigid sidewalk/driveway; and the performance of the insulation layer under truck loads on the sidewalk/driveway.

7. More anti-icing experiments should be conducted to evaluate the cost parameters in a sound statistical manner.

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